HISTORICAL GERMAN CONTRIBUTIONS TO PHYSICS AND APPLICATIONS OF ELECTROMAGNETIC OSCILLATIONS AND WAVES

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The present review summarizes a series of the most important historical contributions of German scientific researchers and industrial companies in Germany to the physics and applications of electromagnetic oscillations and waves during the past 140 years and intends to point out some relations to Russian scientists. The chronology highlights the following scientists: Philipp Reis (*1834-†1874): first telephone; Hermann von Helmholtz (*1821-†1894): unification of different approaches to electrodynamics; Heinrich Hertz (*1857-†1894): fundamental experiments on electromagnetic waves; Karl Ferdinand Braun (*1850-†1918): crystal diode, cathode ray tube, transceiver with coupled resonance circuits; Christian Hülsmeyer (*1881-†1957): rudimentary form of RADAR; Robert von Lieben (*1878-†1913): triode as amplifier in transmitter; Heinrich Barkhausen (*1881-†1956): Barkhausen-Kurz oscillations, first transit-time microwave tube; Manfred von Ardenne (*1907-†1997): first integrated vacuum tube circuits; Hans Erich Hollmann (*1899-†1961): multi-cavity magnetron, principle of reflex klystron; Oskar Heil (*1908-†1994): principle of the klystron, multi-stage depressed collector, patent of field effect transistor (FET); Walter Schottky (*1886-†1976): tetrode electron tube, theory of shot noise, Schottky effect, Schottky barrier; Herbert Kroemer (*1928): III-V semiconductor heterostructures; Jürgen Schneider (*1931): quantum electronic model of electron cyclotron resonance maser.

Introduction

The purpose of this paper is to present a chronology of historical German contributions to the physics of electromagnetic oscillations and waves and their applications to communication, radio, television, RADAR, computer systems and heating.

Often an invention is attributed to one or two persons, the names of whom vary from country to country, depending on the country of origin of the authors. This paper will illustrate that simultaneous development was going on all over the world and to point out some relations of German and Russian scientists.

From 1926-1929, Alexander A. Andronov (*1901-†1952) was a post-graduate student at the Faculty of Physics and Mathematics of the Moscow State University under the supervision of Leonid Isaakovich Mandelstam (*1879-†1944) and developed in his PhD thesis the most general approach to the theory of auto-oscillators. On the other hand, L.I. Mandelstam got his education from 1899-1914 as PhD student, Assistant Professor and University Lecturer in the Institute of Physics of Karl Ferdinand Braun (*1850-†1918) at the University of Straßburg. K.F. Braun was the Nobel Prize Laureate of 1909 in Physics of Electric Oscillations and Radio Telegraphy together with Guglielmo Marconi (*1874-†1937). At the University of Straßburg L.I. Mandelstam became an excellent experimentalist and gifted lecturer. He conducted original research on radio transmitters and receivers and performed fundamental works in optics: scattering in optically uniform and turbid media, theory of dispersion, scattering at liquid surfaces, theory of optical microscope imaging, radiation of sources near the boundary of two liquid media and optical measurements in analogy with radio experimental investigations. In 1912 L.I. Mandelstam became a member of the German Society of Natural and Physical Scientists. In July 1914, just before the beginning of World War I, he and N.D. Papalexy, who also had been an Assistant Professor of K.F. Braun, moved back to Russia where they founded their scientific schools.

These close relations between German and Russian radio telegraphy scientists have been the major motivation for the present article.

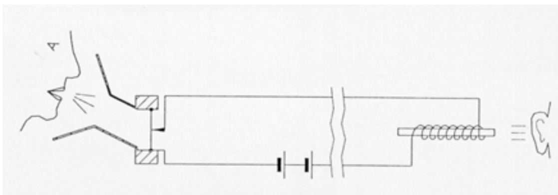
Chronology of Historical German Contributions

1. Philipp Reis: First Telephone

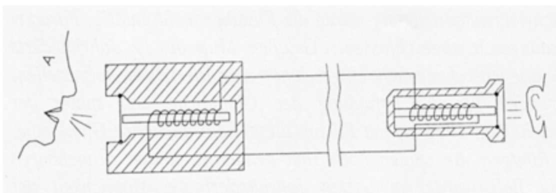
Johann Philipp Reis (*1834-†1874) (Figs. 1 and 2) reported on October 20, 1861 in a seminar in the Senckenberg-Museum at Frankfurt/Main "On the propagation of tones over arbitrary distances via galvanic currents". He demonstrated his apparatus by transmission of the following sentence: "The horse does not eat cucumber salad" [1]. However, this work was not highly regarded in Germany and Reis did not apply for a patent. On February 14, 1876 Alexander Graham Bell (*1847-†1922) took out a patent for the telephone in the USA. Two hours later, at the same day, Elisha Gray (*1835-†1901) also applied in the USA for a patent on telephone but he was refused. Figure 3 shows a comparison of the Reis-Telephone and the Bell-Telephone. In 1877 the Siemens & Halske Company in Berlin started the series production of telephones and in 1882 they built and offered the first wall-mounted device (Werner von Siemens (*1816-†1892) & Johann Georg Halske (*1814-†1890)).

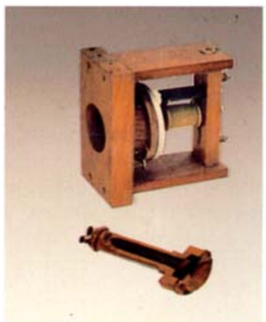
Fig. 1: Philipp Reis

Fig. 2: Philipp Reis testing his telephone in 1861.



"Reis-Telephone" (1861) with
"Knitting Needle Receiver"





"Bell-Telephone" (1876) with permanent
magnet rods and coils

Fig. 3: Comparison of Reis-Telephone and Bell-Telephone.

2. Hermann von Helmholtz: Unification of Different Approaches to Electrodynamics

Hermann Ludwig Ferdinand von Helmholtz (*1821-†1894) was perhaps the last real "Universal Scientist" in the tradition of Gottfried Wilhelm Leibniz (*1646-†1716). From 1842 to 1849 he worked as so-called Eskadron-Surgeon in the Charité at Berlin in several guards regiments at Potsdam and as Lecturer for Anatomy in the Berlin Academy of Arts. His brilliant career as a University Professor started in the spring of 1849 when he became Professor of Anatomy and Physiology at the Albertina in Königsberg (now Kaliningrad). From 1855 to 1858 he had the same function at the University of Bonn. His call to Bonn was initiated by Alexander von Humboldt. In the year 1858 Helmholtz was appointed to the Chair of Physiology at the University of Heidelberg where he was a colleague of the ingenious Robert Wilhelm Bunsen (Chemistry, *1811-†1899) and Gustav Robert Kirchhoff (Physics, *1824-†1887). During these productive years in Heidelberg he finished his intensive research work in the field of Physiology and published his famous "Handbook of Physiological Optics" (3 volumes), treating the 3-colour theory, and his book on the "Theory of Sound Perception". After Heinrich Gustav Magnus (*1802-†1870) passed away, Helmholtz was appointed in 1871 to the Chair of Physics and Mathematics at the University of Berlin (Fig. 4) where he later also was engaged in Philosophy. In the year 1883 he was ennobled. His extraordinay contributions to electrodynamics are described in [2-4]:

In 1847 Helmholtz suggested in his work "On the Conservation of Forces" electrical oscillations 6 years before this process was theoretically calculated by William Thomson (Lord Kelvin, *1824-†1907) (1853) and 10 years before it was experimentally verified by B.W. Feddersen (1857).

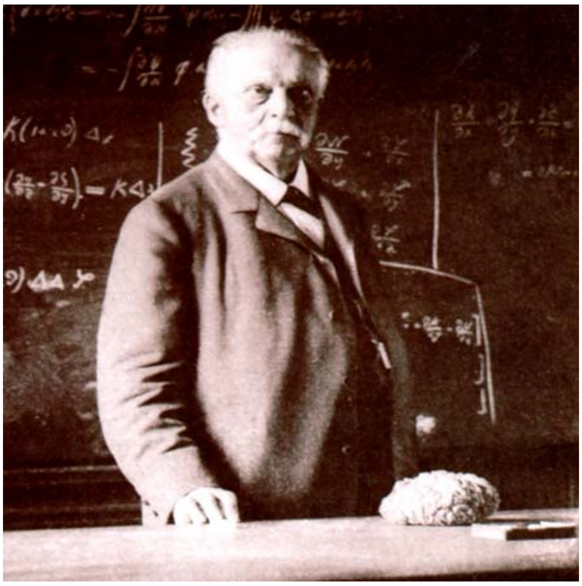


Fig. 4: Hermann von Helmholtz (July 7, 1894).

From 1870 to 1874, Helmholtz tried to unify different approaches to electrodynamics since its overall picture was difficult, incoherent, and not finished. The German Schools of Franz Ernst Neumann (*1798-†1895) and Wilhelm Eduard Weber (*1804-†1891) had developed a comprehensive explanation of both electrodynamics and electromagnetic induction in the classic Newtonian framework of a direct action at distance between charges and currents (i.e. moving charges). They tried to derive induced currents from an energy principle using an electrodynamic interaction potential of two linear conductors (currents). Helmholtz introduced a parameter k as additional term, with

$k = -1$ Weber
$k = 0$ James Clerk Maxwell (*1831-†1879)
$k = +1$ Neumann

The problem in deciding for the correct version was that integration along a closed current loop eliminates the k-dependence.

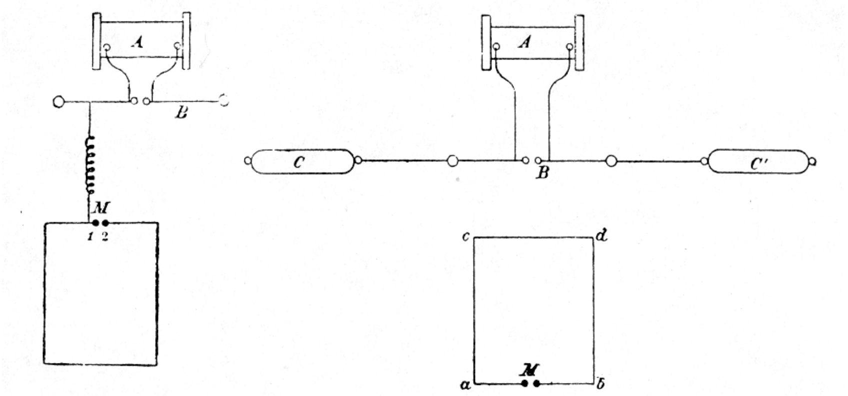
In 1878/79 Helmholtz initiated a student competition of the Philosophical Faculty of the University at Berlin. The winner with distinction was his most outstanding student Heinrich Hertz who proved that electrical charges in time dependent currents do not exhibit inertia, which means that Weber's theory is wrong.

In 1879 Helmholtz initiated an international competition of the Prussian Academy of Sciences: "Do dielectric and galvanic currents have equivalent electrodynamic forces?" The winner again was Heinrich Hertz who confirmed Maxwell's theory with his brilliant epoch making experiments at the Polytechnical University of Karlsruhe (1886-1888, see section 3). Even today, the equations describing electromagnetic waves in homogeneous media (μ and ε are scalars) with no charge and current densities ($\rho = 0$, $\vec{j} = 0$) are called Helmholtz equations.

3. Heinrich Hertz: Discovery of Electromagnetic Waves

Fig. 5: Heinrich Hertz

Heinrich Rudolph Hertz (*1857-†1894) (Fig. 5) was a student of Kirchhoff and Helmholtz at the University of Berlin where he earned on March 15, 1880 his Doctorate in Physics with his dissertation entitled "On induction in rotating spheres". After his Habilitation in May 1883 at the University of Kiel and intensive work on electrodynamics he got the call to be a Full Professor of Physics at the Polytechnical University of Karlsruhe (1885-1889) where he conceived and performed his brilliant fundamental experiments confirming Maxwell's predictions and theory (see section 2) [4]. His classical experimental set-ups are shown in Figs. 6 and 7. Hertz generated, radiated (transmitted) and received (detected) electromagnetic waves at frequencies in the range of 50-500 MHz.



A: Inductorium
B: Spark gap in transmitter circuit
C: Metal spheres at both ends of transmitting antenna
M: Spark gap in receiver circuit ("Nebenfunken")

Fig. 6: Experimental set-ups of Heinrich Hertz (1886).

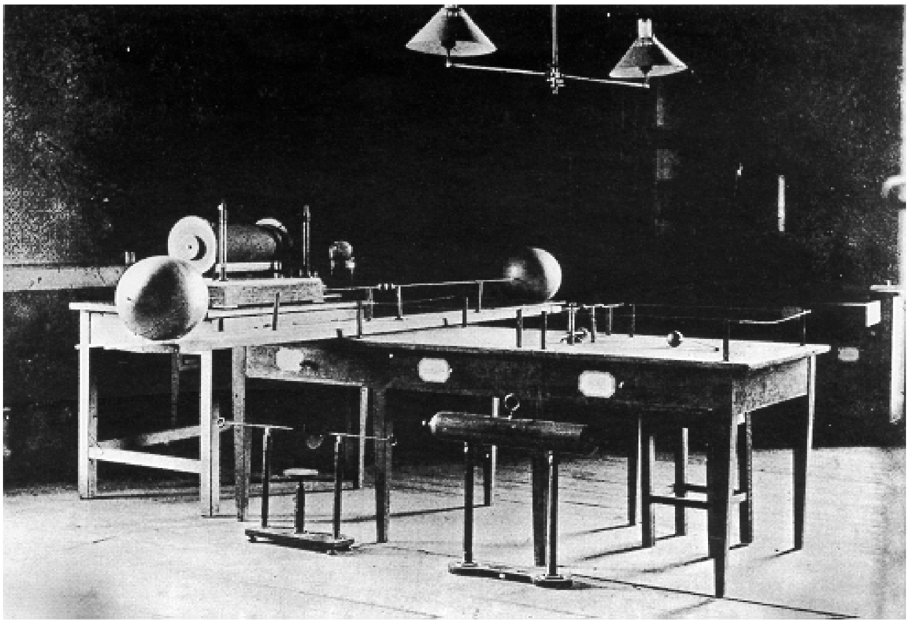


Fig. 7: Original Hertzian oscillator at Institute of Physics of Polytechnical University of Karlsruhe (1886-1888).

His initial experiment was on November 13, 1886, proving wireless transmission between two open circuits over 1.5 m and the decisive paper on the finite velocity of propagation of electromagnetic waves in air ($v_{phase} = c = 1/\sqrt{\mu_o \varepsilon_o}$) was published in 1888. His epoch making experiments conclusively proved the optical properties of electromagnetic waves such as: frequency, wavelength,

amplitude (power), phase, polarization, reflection, refraction, diffraction and interference. He used reflectors at the transmitting and receiving positions to concentrate the waves into a beam.

Maxwell's ideas and equations were expanded, modified and made understandable after his death by the efforts of Hertz and the three "Maxwellians" George Francis FitzGerald (*1851-†1901), Oliver Lodge (*1851-†1940) and Oliver Heaviside (*1850-†1925) [5]. It is important to note that Hertz and the Maxwellians were not aware of each other's work until Hertz published his 1888 work. The Maxwellians appreciated Hertz's brilliant experiments and their implications and gave them the widest possible publicity and labeled them from the beginning as a decisive new confirmation of Maxwell's theory. The four equations in vector notation containing the four electromagnetic field vectors are now commonly known as Maxwell's equations. However, Einstein and Heaviside referred them as Maxwell-Hertz and Maxwell-Heaviside-Hertz equations, respectively. Since Hertz did not know anything about modulation of high frequency electromagnetic waves at low frequencies, he stated that waves with frequencies in the audio range (kHz) have too long wavelength and cannot be focused by reflectors so that they cannot be used for wireless telegraphy.

In 1887 Hertz also discovered the photo electric effect. He observed that the length of the spark between two electrodes increases when ultraviolet light falls on the negative electrode of a spark gap.

In the autumn of 1886 Hertz was offered chairs at the Universities of Gießen, Berlin and Bonn. His choice was Bonn where he became in April 1889 the successor of Rudolf Emanuel Clausius (*1822-†1888) and worked on "Principles of Mechanics" (1891). However, on January 1, 1894 he died at the age of only 37 years owing to a severe ear-, nose- and throat infection connected with a bone disease. H. von Helmholtz stated in his touching obituary: "He is a victim of the envy of the gods".

Fig. 8: Alexander Popov

The Russian Alexander Popov (*1859-†1906) (Fig. 8) demonstrated in 1895 his so-called "Thunderstorm Recorder" using aerial, coherer (invented in 1890 by Edouard Branly (*1844-†1940)) and electromagnetic relay. He succeeded in the transmission of the words "Heinrich Hertz" over a distance of 250 m. The antenna was mounted to a balloon. A few days later, also in 1895, Marconi transmitted and received a coded message over a distance of 1.75 miles and one year later he applied for the first patent in wireless, covering the use of transmitter and coherer connected to a high aerial and earth.

4. Karl Ferdinand Braun: Crystal Diode, Cathode Ray Tube, Wireless Telegraphy

Fig. 9: Ferdinand Braun

The chronology of the professional activities of Karl Ferdinand Braun (*1850-†1918) (Fig. 9) is: 1870-1874: Assistant Professor at the Universities of Berlin and Würzburg (Habilitation supervised by H. v. Helmholtz); 1874-1877: Teacher at the Thomas Gymnasium Leipzig; 1877-1879: Professor at the University of Marburg; 1880-1882: Full Professor at the University of Karlsruhe (Predecessor of H. Hertz); 1885-1895: Full Professor at the University of Tübingen and 1895-1918 Full Professor at the University of Straßburg. In 1874 K.F. Braun discovered conduction and rectification in metal sulfide crystals that occured when the crystal was probed by a metal point (whisker). On November 14, 1876 he demonstrated this rectification effect of a metal-semiconductor contact at Leipzig to a broad audience but his work was not recognized at that time.

Later, his discovery led to the development of crystal radio detectors in the early days of wireless telegraphy and radio (1906).

On February 15, 1897 he invented the cathode ray tube (CRT) with magnetic deflection [6] which in Germany is called "Braun's Tube" (Fig. 10). On September 20, 1898 K.F. Braun discovered the transceiver with two coupled resonance circuits (Fig. 11) (Patent DRP 111578 of October 14, 1898) which act as an impedance transformer allowing much more power compared to Marconi's transmitter. Braun used a loop aerial for transmission and reception of wireless signals [7]. He shared the Nobel Prize for Physics in 1909 with G. Marconi for his contributions to the physics of electric oscillations and radio telegraphy, but during his scientific life he could not verify his dream "Funken ohne Funken" which means "Wireless Telegraphy without Sparks".

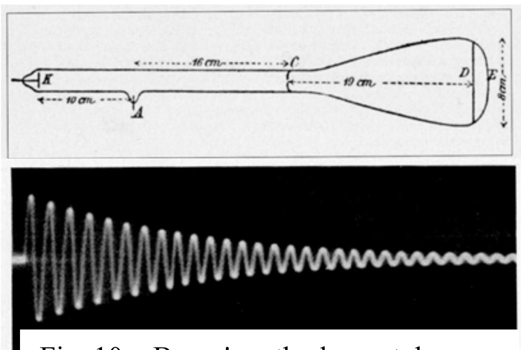


Fig. 10: Braun's cathode ray tube.

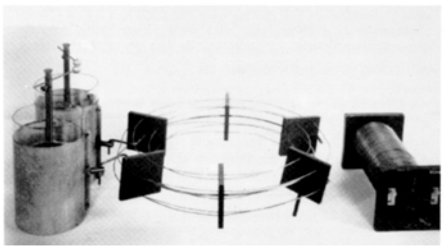


Fig. 11: Braun's transmitter with two Leyden jars and two coupled resonance circuits.

5. Christian Hülsmeyer: Rudimentary Form of RADAR

Christian Hülsmeyer (*1881-†1957), a German inventor fascinated by Hertzian waves, was far ahead of his time. One of many contributors to the development of electromagnetic waves for wireless communications, he got the idea for a different application: "Seeing ships through fog and darkness by transmitting waves and detecting the echoes". On April 30, 1904 he applied for a German Patent on a "Means for reporting distant metallic bodies to an observer by use of electric waves (DRP No. 165546 and later DRP No. 169154), a rudimentary form of RADAR. In Fig. 12 the drawing Fig. 1 of Hülsmeyer's patent is given, showing what application he mainly had in mind. Fig. 13 shows a schematic cross section of the quasi-monostatic system with single frequency operation (1 m wavelength)

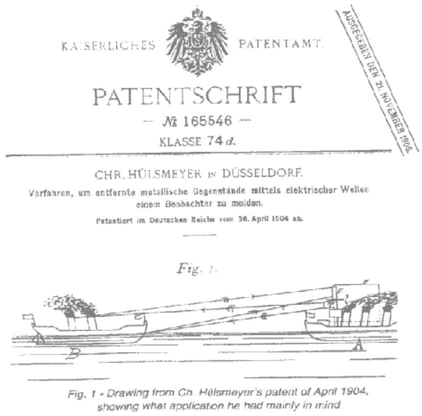


Fig. 12: Drawing from Hülsmeyer's patent of April 30, 1904 showing the application he mainly had in mind.

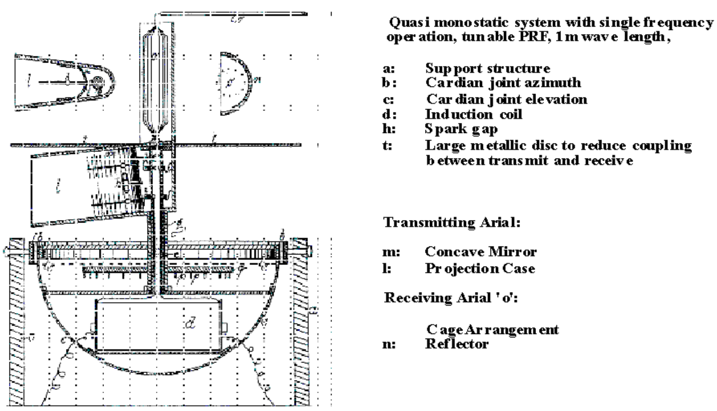


Fig. 13: Schematic of Hülsmeyer's quasi-monostatic RADAR system.

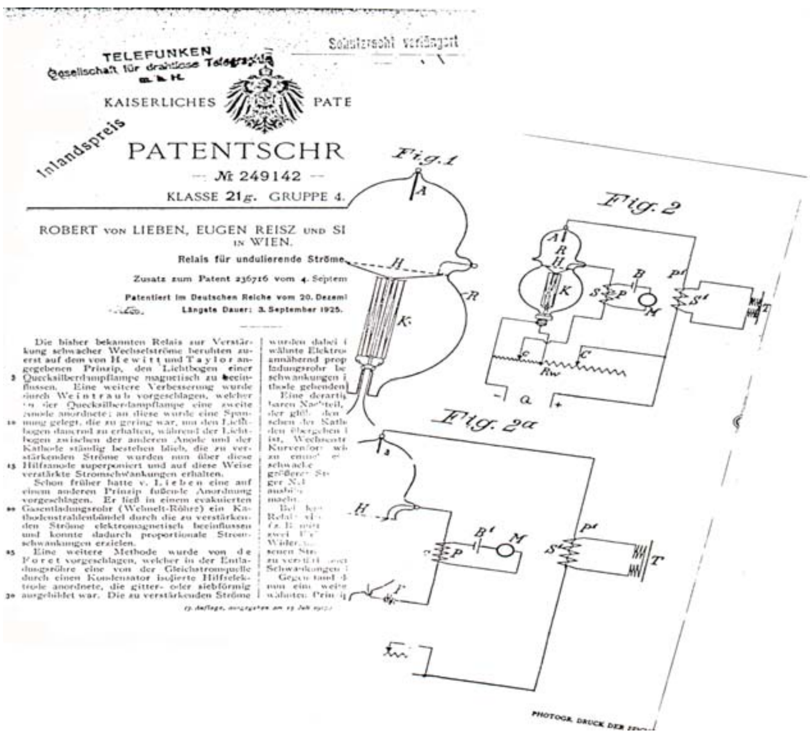
and tunable pulse repetition frequency (PRF), which he called "Telemobiloscope". Though he demonstrated a range of 3000 m, neither shipping nor naval leaders were interested in his invention. Even Telefunken rejected an offer to buy his patent. Around 1930 Hülsmeyer's idea was taken up again, or independently arrived at. At least eight countries developed RADAR systems, but for warning of aircrafts attacks rather than for ship navigation. Robert Alexander Watson-Watt (*1892-†1973) of Scotland patented such a system in 1935. The term RADAR, an acronym of radio detection and ranging, was not proposed until 1940.

6. Robert von Lieben: The Triode as an Amplifier in a Transmitter

The development and production of high vacuum electron tubes started in Germany at Telefunken, the company having been created in 1903 by the joint efforts of AEG and Siemens. Later in 1911 the so-called 'von Lieben Konsortium' was founded by AEG, Siemens, Telefunken and Felten & Guilleaume specifically to evaluate the von Lieben patents [8].

Robert von Lieben (*1878-†1913) was born in Vienna, Austria. In 1906 he obtained a patent for an inertia-less relay using a gas filled amplifier tube which can be denoted as a deflection grid controlled triode. In the same year, in the USA, Lee de Forest (*1873-†1961), the so-called "Father of Radio" invented the transmission grid controlled triode, a triode with a cold grid-like electrode between cathode and anode. This allowed control of the flow of electrons from the heated cathode. Calling it an Audion, de Forest referred to it as a "device for amplifying feeble electric currents" but, as von Lieben, until 1912 he used the triode only for detecting radio waves. On December 20, 1910 Robert von Lieben applied for a patent on the socalled "Lieben Tube" (see Figs. 14, 15 and 16), DRP No. 249142, a transmission grid controlled triode with a Wehnelt cathode. In 1912 engineers were coming to realize that the triode had other uses besides detection of radio waves. Lee de Forest, Fritz Loewenstein and Irving Langmuir in the USA as well as Robert von Lieben and Otto von Bronk in Germany realized that it could be used in a transmitter and could work as an oscillator. These functions were soon put to use. The three-electrode vacuum tube was included in designs for telephone repeaters in several countries.

Also in 1912 Edwin Howard Armstrong (*1890-†1954), a student at Columbia University in New York City, USA, found that he could obtain much higher amplification from a triode by transferring a portion of the current from the anode back to the signal going to the grid (regenerative receiver). He also found that increasing this feedback beyond a certain level made the tube into an oscillator, a generator of continuous waves (CW). At about the same time, others, including Alexander Meißner (*1883-†1953) in Germany, Henry Round in England, and Lee de Forest, created similar circuits. Armstrong himself went on to make other fundamental contributions to radio science such as the superheterodyne circuit (1918) (see section 10) and frequency modulation (FM) techniques. The triode became the basic component for radio, RADAR, television and computer systems until transistors began replacing vacuum electron tubes in the early 1950's [8].



TELEFUNKEN Gesellschaft für drahtlose Telegraphie m. b. H.

Schutzrecht verlängert

KAISERLICHES PATE

Inlandspreis

PATENTSCHR

— № 249142 —

KLASSE 21g. GRUPPE 4.

ROBERT VON LIEBEN, EUGEN REISZ UND SI
IN WIEN.

Relais für undulierende Ströme

Zusatz zum Patent 236716 vom 4. Septem

Patentiert im Deutschen Reiche vom 20. Dezem

Längste Dauer: 3. September 1925.

Die bisher bekannten Relais zur Verstärkung schwacher Wechselströme beruhten zuerst auf dem von Hewitt und Taylor angegebenen Prinzip, den Lichtbogen einer Quecksilberdampflampe magnetisch zu beeinflussen. Eine weitere Verbesserung wurde durch Weintraub vorgeschlagen, welcher in der Quecksilberdampflampe eine zweite Anode anordnete; an diese wurde eine Spannung gelegt, die zu gering war, um den Lichtbogen dauernd zu erhalten, während der Lichtbogen zwischen der anderen Anode und der Kathode ständig bestehen blieb, die zu verstärkenden Ströme wurden nun über diese Hilfsanode superponiert und auf diese Weise verstärkte Stromschwankungen erhalten.

Schon früher hatte v. Lieben eine auf einem anderen Prinzip fußende Anordnung vorgeschlagen. Er ließ in einem evakuierten Gasentladungsrohr (Wehnelt-Röhre) ein Kathodenstrahlenbündel durch die zu verstärkenden Ströme elektromagnetisch beeinflussen und konnte dadurch proportionale Stromschwankungen erzielen.

Eine weitere Methode wurde von de Forest vorgeschlagen, welcher in der Entladungsröhre eine von der Gleichstromquelle durch einen Kondensator isolierte Hilfselektrode anordnete, die gitter- oder siebförmig ausgebildet war. Die zu verstärkenden Ströme

Fig. 14: The Lieben patent of December 20, 1910.

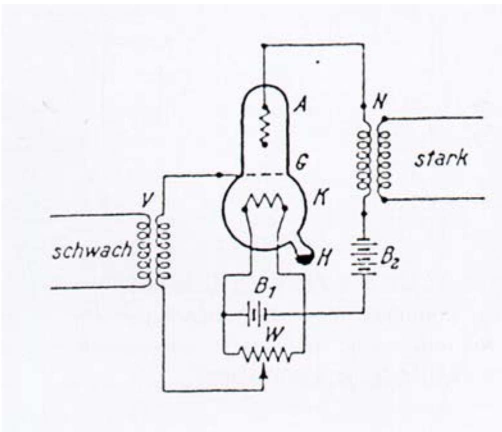


Fig. 15: Circuitary for the Lieben tube.

Fig. 16: The big Lieben tube (height: 315 mm).

7. Heinrich Barkhausen: First Transit Time Microwave Tube

The retarding-field tube (or reflex triode) can be regarded as the first transit-time tube. It was invented by H. Barkhausen (*1881-†1956) (Fig. 17) in 1920. During some measurements on a triode with a positive grid and a negative anode (Fig. 18) Barkhausen and K. Kurz noticed irregularly fluctuating anode currents. Barkhausen interpreted them as self-excited oscillations generated by the tube [8,9]. Later they were known as "electron dance oscillations" on account of the oscillatory motion of the electrons around the wires of the grid. Due to the existence of a retarding field between the grid and the anode the name 'retarding-field tube' was generally adopted. It is interesting to note that the three effects characteristic of transit-time devices are already present in the retarding field tube: they are velocity modulation, bunching (i.e. conversion of velocity into

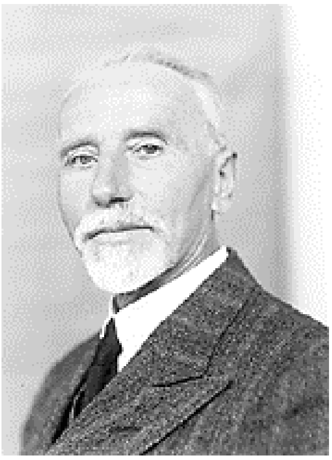


Fig. 17: Heinrich Barkhausen

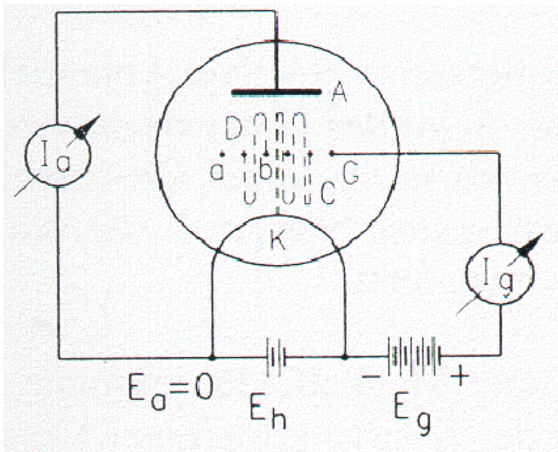


Fig. 18: Retarding-field tube and its circuit.

density modulation) and power transfer from the beam to the circuit. The principle can also be described by extraction of "wrong phase" electrons and negative absorption by a stationary ensemble of non-isochronous oscillators [10].

This was the first tube in which the unavoidable transit time effect was put to good use. In 1920 the shortest wavelength which could be reached using commercially available triodes was 43 cm. Owing to their simple design, such reflex triode oscillators became very popular, especially among university institutes. They were mostly used as high frequency local oscillators and sources of oscillations for various measuring instruments (0.3-6.4 GHz at 5 W – few mW). In order to achieve higher frequencies and higher output powers early variants of the original Barkhausen tube, which had no separate resonant circuit, were investigated. The world's first decimeter transmitter and receiver was built and operated in 1931 by Hans Erich Hollmann [11] at the Heinrich Hertz Institute in Berlin. The unit worked by using a symmetric opposed, resonant Lecher circuit excited by a so-called "hammer" retarding field tube (see Fig. 19). Later only reflex klystrons were

used as local oscillators. The socalled Vircator (Virtual Cathode Oscillator) is a modern version of the retarding-field tube [10].

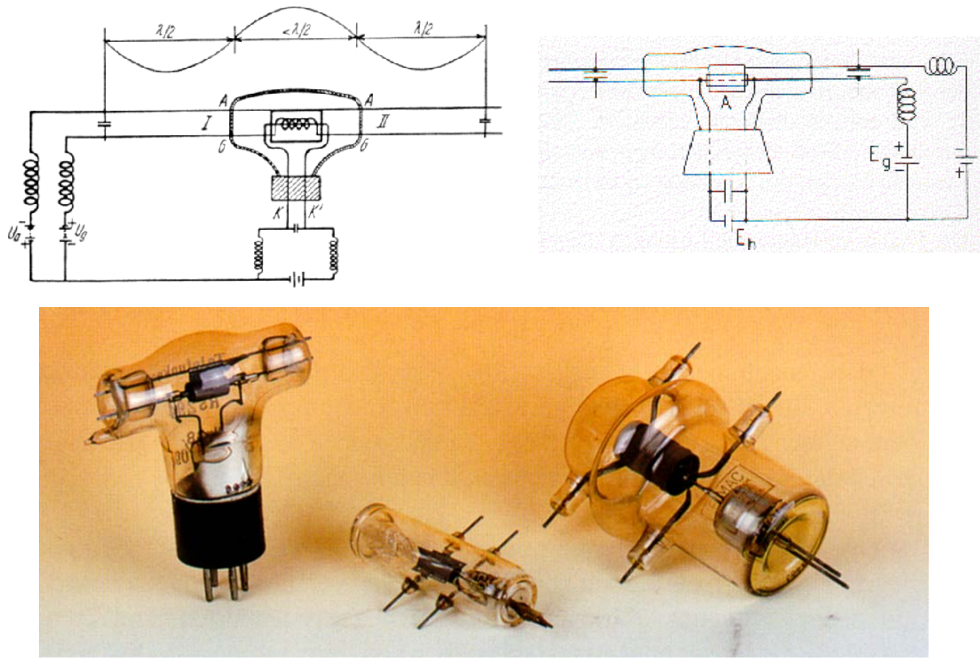


Fig. 19: Retarding-field tube RS296 and its circuit (Kühle 1932 at Telefunken) "Hammer Tube" [8,11]. The photograph also shows the retarding field tubes 8012 of RCA (middle) and VT 127 A of Eimac (right).

8. Manfred von Ardenne: First Integrated Vacuum Tube Circuits

Manfred v. Ardenne (*1907-†1997) was younger than 15 years when he first met Siegmund Loewe (*1885-†1962), the owner of the Loewe Radio Company in Berlin-Steglitz who later introduced the quartz crystal as a frequency standard in electronic circuits.

M. v. Ardenne and H. Heinert developed in Loewe's Company the so-called Loewe-3 fold tube 3NF (3 triodes) [12] in which the audion (receiver), the resistive amplifier (RC amplifier), the output amplifier and the coupling capacitors and anode resistors where integrated into a single vacuum tube (patent 1924, first 3NF 1925). Only a few months later they developed the Loewe 2-fold tube 2 HF (2 triodes with common space-charge grid) for broadband amplifiers (in 1926). The circuit diagram of the "five-in-two" receiver and the photograph of a selection of Loewe tubes are shown in Figs. 20 and 21. Note that the two tubes are coupled through the tuned-radio-frequency transformer composed of coils L_3 and L_4 and the condenser C_2. The first stage of RF amplification is resistance-coupled. Figures 22 and 23 show the autodidact M. v. Ardenne together with Lee de Forest

(in 1926) and together with Siegmund Loewe and the first broadband amplifier (in 1928), respectively.

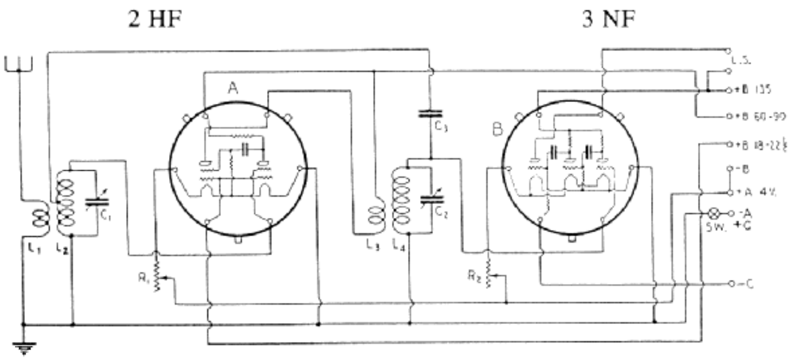


Fig. 20: Circuit diagram of the "five-in-two"-receiver. Note that the two tubes are coupled through the tuned-radio-frequency transformer composed of coils L_3 and L_4 and the condenser C_2. The first stage of RF amplification is resistance-coupled.

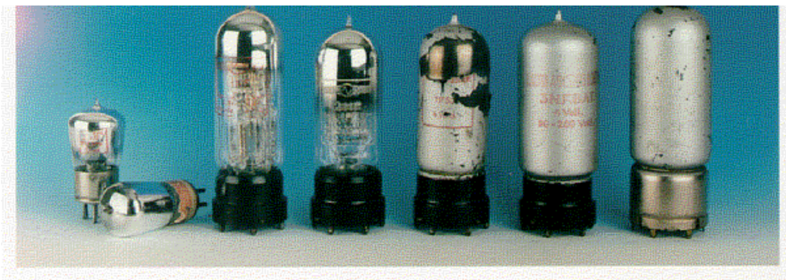


Fig. 21: Selection of Loewe tubes.

Fig. 22: M.v. Ardenne (1926) together with Lee de Forest (*1873-†1961).

Fig. 23: M.v. Ardenne (1928) together with Siegmund Loewe and the first broadband amplifier.

9. Hans Erich Hollmann: Multy-Cavity Magnetron, Principle of Reflex Klystron

In 1921 Albert W. Hull at General Electric Co. investigated the motion of electrons in a cylindrical diode under the influence of a homogeneous axial magnetic field. He noticed the possibility to control the electron current to the anode by variation of the magnetic field. Hull wanted to develop for his company a magnetically controlled relay or amplifier in competition to the grid controlled triodes of Western Electric Co., but also noted the possibility of RF generation. He called his novel device "magnetron". The magnetron for high frequency oscillations was independently investigated in 1924 by Erich Habann in Jena [13] and Napsal August Zázek in Prague [14]. Habann correctly predicted the conditions required for the appearance of a negative resistance which would overcome the usual damping caused by the resonant circuit losses. In contrast to the Hull device, Habann employed a magnetic field which was constant in time like in today's magnetrons. Using his split-anode magnetron (Fig. 24, left) Habann was able to generate oscillations in the 100 MHz range. Zázek developed a magnetron with a solid cylindrical anode and generated frequencies up to 1 GHz. The breakthrough in generation of cm-waves by magnetrons came in 1929 when K. Okabe operated his slotted-anode magnetron (5.35 GHz) at Tohoku University in Sendai, Japan. Hans Erich Hollmann filed in Germany on November 27, 1935, a patent on the multi-cavity magnetron. US Patent 2,123,728 was granted on July 12, 1938 (Fig. 24, right), well ahead of J. Randall's and H. Boot's work in February 1940. The operation principle of a reflex klystron was anticipated by Hollmann as early as 1929 who patented a "double-grid retarding-field tube" [11].

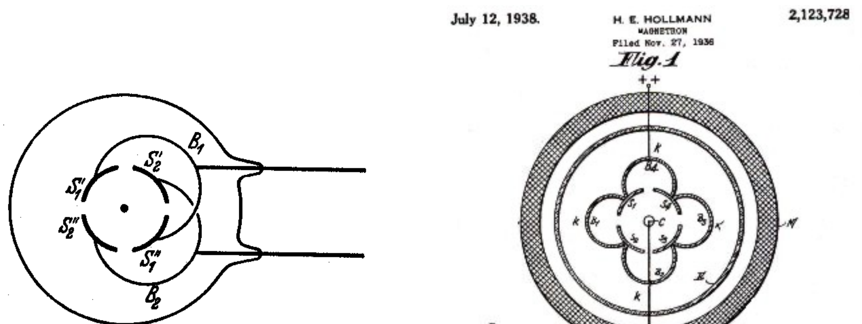


Fig. 24: Schematics of Habann's split-anode magnetron (left) and Hollmann's multi-cavity magnetron (right).

10. Oskar Ernst Heil: Field Effect Transistor, Principle of Klystron

Oskar Ernst Heil (*1908-†1994) was a peripatetic German scientist, who earned his Doctorate in Physics at the University of Göttingen in 1933. There he met and married Agnesa Arsenjeva (*1901-†1991), a promising young Russian physicist (Fig. 25) who also got her PhD from the University of Göttingen (1928).

Fig. 25: Oskar Heil and Agnesa Arsenjewa-Heil in Bormio, Italy (1935).

Together, the Heils travelled to the UK and worked with Lord Rutherford at the Cavendish Laboratory in Cambridge. On March 2, 1934 O. Heil applied for a patent on "Improvements in, or relating to electrical amplifiers and other control arrangements and devices" (British Patent No. 439457) which can be seen as the theoretical invention of the capacitive current control in field effect transistors (FETs). During a trip to Italy A. Arsenjeva-Heil and O. Heil wrote in Bormio a publication entitled "On a new method for producing short, undamped electromagnetic waves of high intensity" (in German) which was published in the Zeitschrift für Physik 95, 1935, pp. 752-762. This publication gives the first description of the fundamental principles behind modern high power linear beam microwave electron tubes: They described a transit-time tube in which the three characteristic features velocity modulation, phase focusing and energy transfer were designed to occur in three separate regions, an arrangement which is also characteristic of a klystron. Further they demonstrated, in my opinion for the first time, that it is necessary, in order to achieve high RF power output, to use a linear electron beam and that the beam must be positioned in such a way as to prevent the electrons from landing on RF electrodes – they must only be allowed to penetrate the fringe field of the RF electrodes, finally landing on a separate electrode, now called the collector. This arrangement made it possible to separate high frequency from beam guiding electrodes, thus permitting the use of high power electron beams (Fig. 26).

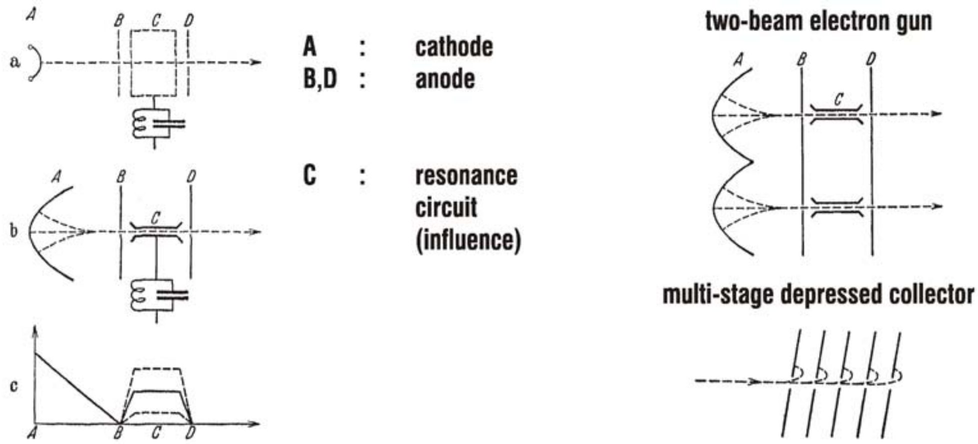


Fig. 26: Original drawings (Figs. 1, 9 and 10) from the Heils' publication.

In addition, the authors propose a two-beam electron gun and a multistage depressed collector (Fig. 26) for efficiency enhancement by the use of a step-wise reduced voltage collector, a technique which is now commonly used in high power microwave tubes.

Almost immediately afterwards, the by now classical paper of R.H. Varian and S.E. Varian (1939) [15] became available in Germany and klystron research was begun at several industrial and government research laboratories.

It is unlikely that W.W. Hansen and the Varian brothers, Russell, a physicist, and Sigurd a former barnstormer and Pan-American pilot in the USA were aware of the Heils' work on velocity modulation. However, approximately two years after the Heils' paper was published in Germany, Russel "had an idea in the middle of the night" in which he visualized the movement and bunching of cars at different speeds on a highway. This amounted to the velocity modulation concept. Using reentrant versions of the "Hansen Rumbatron" cavity [16], the Varians constructed at the Physics Department of Stanford University several models of a two cavity oscillator and the modern microwave tube was born. It was named "klystron" after an ancient Greek verb indicating waves washing on a shore.

O. Heil apparently joined A. Arsenjeva-Heil when she returned to the Leningrad Physico-Chemical Institute in the USSR. The research on velocity modulation was carried out there, although it did not result in a working device. Presumably because his wife was not allowed out of the Soviet Union again, Heil returned to the UK alone and continued his work on "coaxial-line oscillators," as the British named them, at Standard Telephone and Cables (STC). Just before World War II (WW II) broke out, he slipped back into Germany without finishing his work at STC. He was apparently successful in completing development of his microwave oscillator at C. Lorenz AG in Berlin Tempelhof (Fig. 27). The Germans used his so-called "Heil Generator" tube in WW II [8, 17].

After 1947 O. Heil worked at different universities, research institutes and companies in the USA.

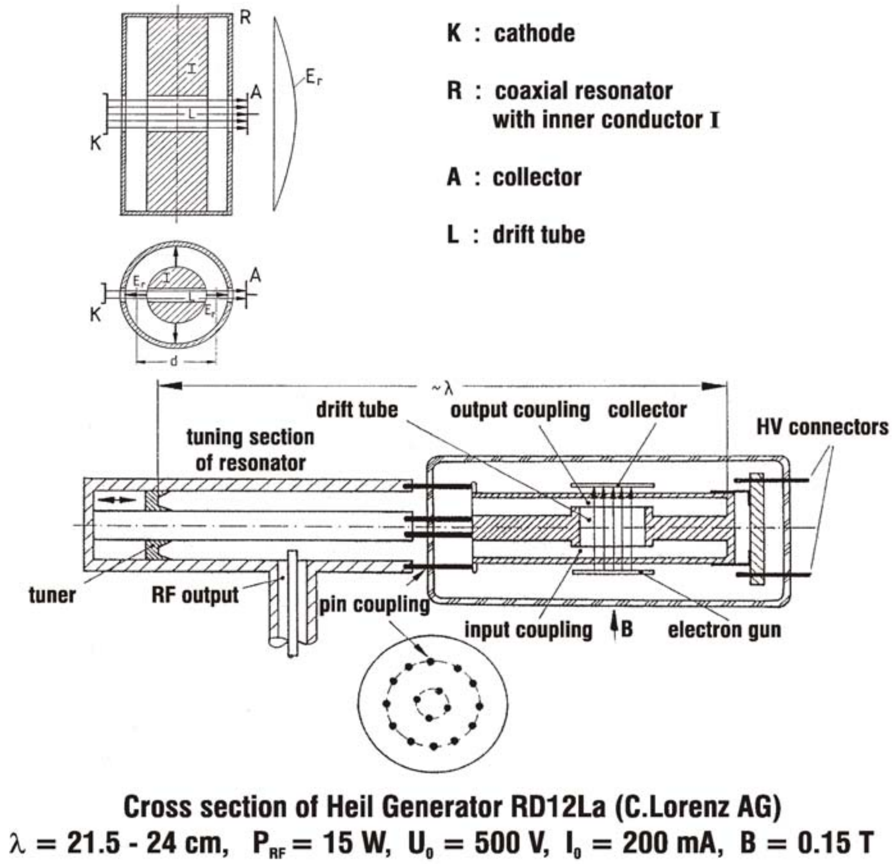


Fig. 27: The Heil Generator (coaxial-line oscillator) [17].

11. Walter Schottky: Tetrode, Theory of Shot-Noise, Schottky Barrier

Fig. 28: Walter Schottky (1961)

Walter Schottky (*1886-†1976) (Fig. 28) was born in Zürich, Switzerland. During 1912-1915 he worked as an Assistant Professor with Max Wien in Jena, from 1916-1919 as a Research Scientist with Siemens & Halske Company in Berlin, 1920-1922 as Privatdozent (Habilitation in 1920) at the University of Würzburg with Wilhelm Wien (*1864-†1928) from 1923-1927 as Full Professor for Theoretical Physics at the University of Rostock and from 1927-1951 as Research Leader with Siemens & Halske in Berlin and Siemens-Schuckert-Company in Berlin and Erlangen. We can see in him a real pioneer of electronics. His most important scientific achievements are [18]:

1914: Discovery of the Schottky Effect: Reduction of electron work function by an electric field
1915/16: Development of space-charge-grid tube and screen-grid tube (Tetrode)
1918: Invention of superheterodyne detection principle, independent of E.H. Armstrong (see section 6),
Theory of shot noise and thermodynamics of electrons
1929: Experimental verification of barrier layer in metal-semiconductor contact (Schottky Barrier)
1938/39: Development of space-charge and edge-sheet theory of crystal rectifiers.

We should not forget that a great part of his work was accompannied by his "Mathematical Assistant" Eberhard Spenke (*1905-†1992).

12. Herbert Kroemer: III-V Semiconductor Heterostructures

Fig. 29: Herbert Kroemer

The 2000 Nobel Prize in Physics honored three scientists for their work in information and communication technology. Herbert Kroemer (Fig. 29) [19] and Zhores Ivanovich Alferov [20] were recognized for developing semiconductor hetero-structures used in high-speed microwave and opto-electronics (that operate continuously at room temperature), ranging from satellite communications to mobile phones and lasers used in CD players. Jack St. Clair Kilby was honored for his part in the invention of the integrated semi-conductor circuit (Ge).

Kroemer, who holds a Ph.D. in theoretical physics from the University of Göttingen, Germany, was born in 1928 (Weimar, Germany). His dissertation on Germanium transistors discussed electron transport in high electrical fields.

Kroemer's career began in 1952, when he became the "house theorist" in the semi-conductor research group of the telecommunications laboratory of the German Postal Service. During this time, he began to wonder why emerging junction transistors did not compare in speed to the earlier point transistors. This led him to the question, "How can an electric field be built into the base region of a junction transistor?" Kroemer realized that one possible way to do this was by not using a single semiconductor, but a graded base region that started with one material and ended in another with a continuous transition between the two. Despite his brave idea, nothing materialized initially because at that time no substantial data had been gathered on semiconductors.

In 1957, while at RCA's David Sarnoff Research Center in Princeton, N.J., USA, Kroemer originated the concept of the heterostructure bipolar transistor. He found his earlier ideas could be expanded when he learned that composition gradients acted as forces on electrons. Kroemer left RCA in 1957 and returned to Germany becoming head of a semiconductor group at Philips Research Laboratory in Hamburg where he pushed for work on GaAs.

In 1959 Kroemer went to work for Varian Associates in Palo Alto, Calif., USA. From this year to 1966 his work yielded the invention of the double heterostructure laser. After submitting in 1963 a paper containing his ideas to the journal *Applied Physics Letters* and having it rejected, Kroemer presented his Nobel Prize-winning work to the *Proceedings of the IEEE*, where it was published under the title "A Proposed Class of Heterojunction Injection Lasers". He also filed for a patent (issued in 1967, expired in 1985) and received an inventor's award of US $100!

"I was told not to work on light-emitting semiconductors because my ideas were judged on the basis of then existing applications," Kroemer noted. "When you look at the history of technology, you see that the principal applications do not evolve incrementally, but are created by the technology. Until you come up with such applications," he said, "you cannot judge how promising technology is. It is foolish to ask immediately what a new technology is good for."

In 1964 Kroemer was the first to publish an explanation of the Gunn Effect. After working for the University of Colorado, Boulder, Colo., Kroemer joined the University of California, Santa Barbara, Calif. (UCSB), in 1976. Initially, Kroemer thought UCSB would never catch up to the leaders in silicon technology, but at the advice of Electrical Engineering and Computer Science Department chair Ed Stear, he was asked to focus all his efforts on developing compound semiconductor technology. The result has earned him a Nobel Prize.

13. Jürgen Schneider: QE Model of Electron Cyclotron Maser

Fig. 30: Jürgen Schneider

Jürgen Schneider (*1931) (Fig. 30) who got his Ph.D. in Physics from the University of Freiburg, Germany, in 1957 moved in the same year to Duke University in Durham, North Carolina, USA, in order to perform research on basics in the field of microwave spectroscopy. There he published his work "Stimulated Emission of Radiation by Relativistic Electrons in a Magnetic Field", Phys. Rev. Lett. 2 (1959), 504, which, together with a paper of the Australian R.Q. Twiss (1958) [21], is the first publication on the quantum electronic (QE) model of the electron cyclotron resonance maser interaction. Neglecting the electron spin, he solved the relativistic Schrödinger equation for the electron motion perpendicular to a magnetic field B_o and obtained a discrete spectrum of the kinetic electron energy, the so-called Landau levels of a non-harmonic oscillator:

$$E_n = m_o c^2 \left[\sqrt{1 + 2\left(n + \frac{1}{2}\right)\frac{\hbar\omega_{co}}{m_o c^2}} - 1 \right] \qquad (1)$$

where m_o is the electron rest mass, c the velocity of light, ħ the Planck constant divided by 2 π and $\omega_{co} = eB_o/m_o$ the nonrelativistic electron cyclotron resonance frequency. These Landau levels are nonequidistant with a decreasing energy gap for increasing quantum number n:

$$E_n - E_{n-1} > E_{n+1} - E_n \quad (2)$$

with

$$\omega_{n+1} \approx \omega_{co}\left[1 - n\frac{\hbar\omega_{co}}{m_o c^2}\right] \quad (3)$$

An external transverse electric RF field with $\omega_{RF} \geq \omega_{n+1}$ can lead to stimulated emission (negative absorption, see Fig. 31) of cyclotron radiation (bremsstrahlung) since the quantum electronic probability for electric dipole transitions scales with ω^3. Due to the very small different energy gaps between neighboring Landau levels and their natural widths, multi-photon transitions can produce powerful microwaves at short wavelengths. However, at a typical electron energy of 80 keV and a frequency of 100 GHz we have $\hbar\omega_{co} = 0.41$ meV and $n \approx 2 \cdot 10^8$ so that Bohr's Correspondence Principle allows a classical description of high power cyclotron resonance masers such as gyrotrons [22, 23].

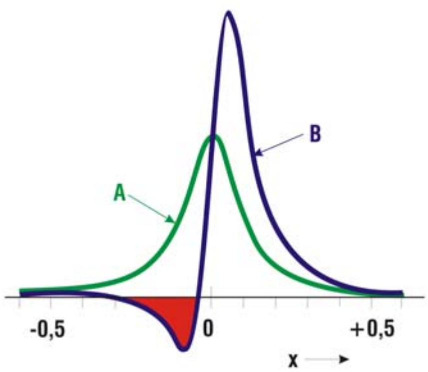


Fig. 31: Cyclotron resonance absorption of electrons ($x = (\omega_{n+1}-\omega_{RF})\,\tau$), non-relativistic (A) relativistic (B).

Gyrotron oscillators (gyromonotrons) are mainly used as high power millimeter wave sources for electron cyclotron resonance heating (ECRH), electron cyclotron current drive (ECCD), stability control and diagnostics of magnetically confined plasmas for generation of energy by controlled thermonuclear fusion [24]. The maximum pulse length of commercially available 1 MW gyrotrons employing synthetic diamond output windows is 5 s at 110 GHz (CPI and JAERI-TOSHIBA), 12 s at 140 GHz (FZK-CRPP-CEA-TED) and 9 s at 170 GHz (JAERI-TOSHIBA), with efficiencies slightly above 30%. Total efficiencies of 45-50 % have been

obtained using single-stage depressed collectors (for energy recovery). The energy world record of 160 MJ (0.89 MW at 180 s pulse length and 140 GHz) at power levels higher than 0.8 MW has been achieved by the European FZK-CRPP-CEA-TED collaboration at FZK where the pulse length restriction to 180 s is due to the HV power supply at $I_{beam} \approx 40$ A. At lower beam current ($I_{beam} = 26$ A) it was even possible to obtain 506 MJ (0.54 MW for 937 s). The longest shot lasted for 1300 s at 0.26 MW output power. These very long pulses were limited by a pressure increase in the tube. A maximum output power of 1.2 MW in 4.1 s pulses was generated with the JAERI-TOSHIBA 110 GHz gyrotron. The Russian and the Japan 170 GHz ITER gyrotrons achieved 0.54 MW at 80s pulse duration and 0.5 MW at 100 s, respectively. Diagnostic gyrotrons deliver $P_{out} = 40$ kW with $\tau = 40$ μs at frequencies up to 650 GHz ($\eta \geq 4\%$). Gyrotron oscillators have also been successfully used in materials processing. Such technological applications require gyrotrons with the following parameters: $f \geq 24$ GHz , P_{out} = 10-50 kW, CW, $\eta \geq 30\%$.

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